P4.2 1DVAR ANALYSIS OF TEMPERATURE AND HUMIDITY USING GPS RADIO OCCULTATION DATA

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1. INTRODUCTION

The *Global Positioning System* (GPS) enables positioning with a very small receiver. The signals transmitted by the GPS satellites are sensitive to the atmosphere and can be used to perform soundings with the radio occultation technique (*e.g.*, Kursinski *et al.*, 1997). The GPS signal can be converted to refractivity N via the Abel transform. The refractivity can then be related to atmospheric pressure P, temperature T, and water vapor partial pressure P_w. the GPS measurement (between 0.5 and 1.5 km), its self-calibration, and its nearly all-weather capabilities make it a good candidate for use in data assimilation systems (DAS) and numerical weather prediction (NWP). In order to demonstrate its usefulness in a DAS or NWP system, a first step is to assess its impact on the analysis. A one-dimensional variational off-line analysis (1DVAR), meaning the data are not assimilated in the 3D DAS, constitutes a starting approach to which further enhancements can be made.

The chosen observable to be analyzed in this study is the refractivity. One way to extract temperature (humidity) from the refractivity, is to assume a humidity (temperature) profile. One variable may then be retrieved without any *a priori* information. The 1DVAR approach used here resolves the ambiguity problem raised in the interpretation of these data. It enables retrieving these two atmospheric variables at a reasonable computing cost.

2. THE RETRIEVAL TECHNIQUE

The retrieval method used here is the minimum variance solution (*e.g.* Rodgers, 1976; Eyre *et al.*, 1993), solved by a quasi-Newton iteration, *i.e.*,

$$x_i = x^b + (H_i^T R^{-1} H_i + B^{-1})^{-1} H_i^T R^{-1} \\ (y - h(x_i) + H_i(x_i - x^b)) \qquad (1)$$

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where i denotes the iteration number, x_i is the current state vector estimate, x^b is the background or first guess, h is an observation operator relating the state variables to the observable and H is its linearized version, y is the observation vector, and B and R are the error covariances of the background and observations, respectively. The background and the observation errors are assumed to be unbiased and uncorrelated with respect to eachother.

The state vector x, which contains the temperature and the humidity at various levels, is first set equal to the guess. After convergence of the iterative process, it represents a solution (the *analysis*) that has an optimal position with respect to both the observations y and the background x^b. This notion of distance is defined in terms of a weighted sum involving the error covariance matrices of the guess B and the observations R. It represents a physical constraint that helps to select one solution among the infinite number of possible atmospheric profiles that would match the observations.

A one-dimensional (1D) forward operator h has been developed. It calculates the refractivity induced by the background information at the altitudes of the GPS observation. The refractivity, after ionospheric correction and neglecting liquid water (valid in most cases), is related to atmospheric parameters by

$$N = b_1 \frac{P}{T} + b_2 \frac{P_w}{T^2}, \qquad (2)$$

where b_1 and b_2 are constants. The operator must then relate the refractivities on the analysis levels to the altitudes and location of the observation. The computation of the Jacobian matrix (H) is also needed in the retrieval. An exact calculation from the analytic derivative of the forward model was verified by comparison with a calculation from finite differences.

The principal sources of error in the GPS refractivity measurements are the result of an imperfect ionospheric correction, the spherical symmetry approximation in the Abel transform, and noise in

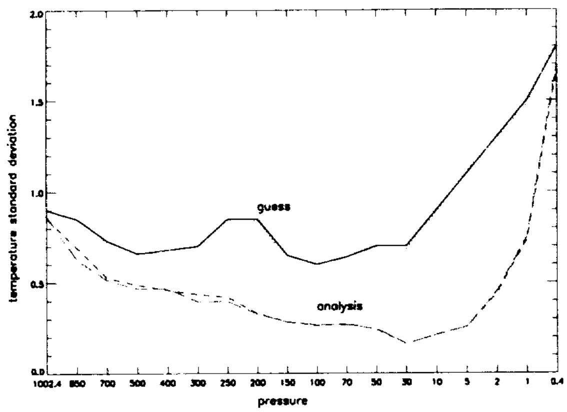

Figure 1: Theoretical standard deviation of analysis errors for temperature. Linear analysis - *plain line*: guess, *short dashes*: analysis; Monte-Carlo simulation - *dotted line*: guess, *long dashes*: analysis.

the phase shift measurements (Kursinski *et al.*, 1997). The errors in refractivity are assumed to be 2% below 5 km altitude and 0.2% above. For the background, we used the error covariance matrix of Joiner and Rokke (1999).

3. THEORETICAL SENSITIVITY SIMULATION

Temperature and humidity retrieval (analysis) errors can be estimated in advance, even before having any real data, by using a linear error analysis (Rodgers, 1990). To validate this linear analysis, we also performed a fully non-linear Monte-Carlo simulation. In this simulation, we analyzed one thousand profiles for each of three typical atmospheric profiles at different latitudes. Errors were added to the background according to the assumed error covariance. Errors were similarly added to the observations. The results for temperature, shown in Figure 1, indicate that an analysis with GPS data should provide a significant improvement as compared with the background. This result holds for all three latitudes.

Figure 2 shows that the maximum impact for the humidity is to be expected in the lower troposphere in the Tropics. This is where the water vapor content is large enough to have a significant influence on the GPS refractivities. The Monte-Carlo approach verifies that the 1DVAR system works properly and that the linear error analysis is accurate. Similar results have been obtained by Healy and Eyre (1999).

4. RETRIEVAL SENSITIVITIES

GPS radio occultation data were collected in 1995 as part of the GPS/MET experiment. Approximately 800 occultations were collected during a time period known as 'Prime Time 3' (June-July 1995, when the encryption was turned off). They are analyzed in the framework of the 1DVAR technique described above using a 6 hour GEOS-Strat forecast as the background. The GEOS-collocated profiles are obtained by interpolating bi-linearly between four grid points. This grid spacing is 2° latitude × 2.5° longitude. Each observation is assumed to have taken place at the center of the 6-hour analysis window. In order to evaluate the impact of the GPS data, profiles of nearby radiosondes are also available.

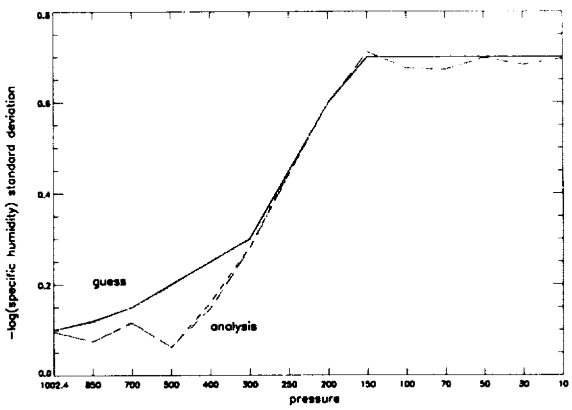

Figure 2: Similar to figure 1 except for $-\log$ specific humidity for a tropical profile.

The first analyses were performed on the 18 GEOS analysis levels. These analyses revealed the necessity of analyzing on more vertical levels, so that the small-scale structures seen by the GPS can be fully resolved. All subsequent analyses were performed on the 46 sigma levels of the GEOS model.

One unexpected result was the sensitivity of the analysis to the gravitational constant used in the analysis. Using different approximations for g can lead to differences of the order of 1K, (see figures 3-4). This feature, specific to the GPS measurements, is related to the forward operator which maps atmospheric parameters from a set of pressures onto a set of altitudes.

The analyses were also found to be sensitive to the surface level pressure. By adding surface pressure to the state vector, any discrepancies in the definition of surface pressure (from the observation preprocessing and the background) are removed. The comparisons with radiosondes were improved with this new degree of freedom. The 1DVAR is able to move the whole refractivity profile downwards or upwards in terms of pressure in order to bring it closer to the observation, without having to modify the temperature at all the levels. This problem is intrinsic to GPS measurements. It is due to the fact that the

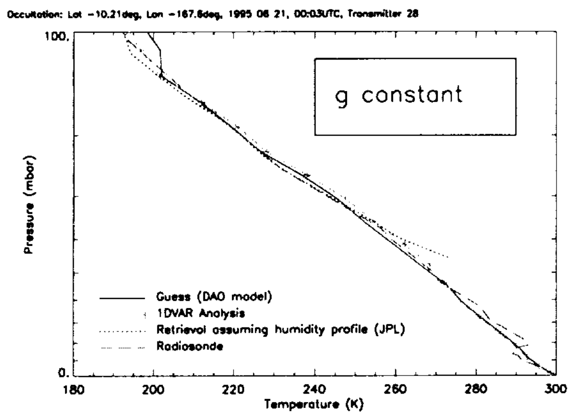

Figure 3: 1DVAR analysis with $g = g_0$

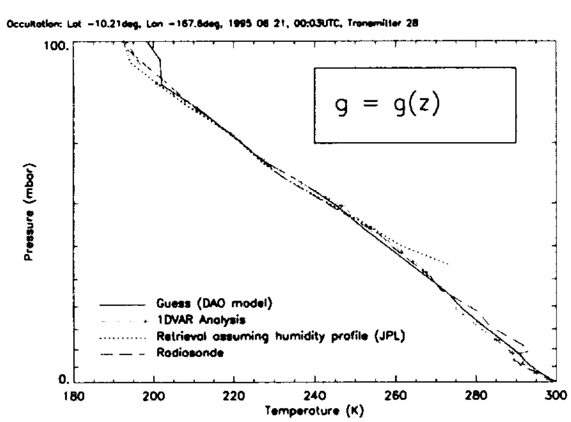

Figure 4: Similar to Figure 3 but with g as a function of height.

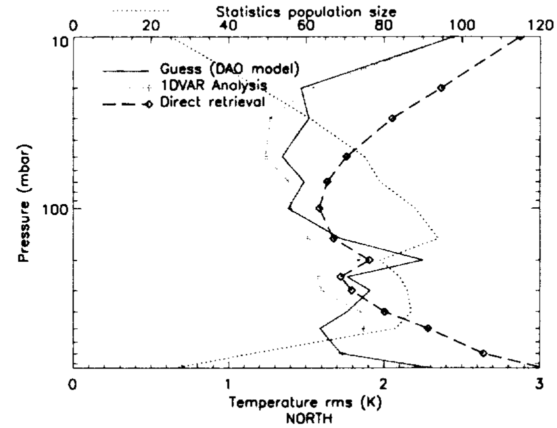

Figure 5: Statistics on temperature comparisons with radiosondes (+/- 3 hours, less than 280 km), n. hemisphere.

background, expressed in terms of pressure levels, is confronted with observations in terms of altimetric levels and hence requires a reference to make the conversion.

5. RADIOSONDE COMPARISONS

A validation study is performed using collocated radiosondes (RS). We compare the differences between the analyses and nearby radiosondes on the one hand, and between the corresponding guess and the same radiosondes on the other hand. The RS collocation criteria are adjusted in order to find a good compromise between representativeness and the number of available profiles. With typical criteria (+/- 3 hours, chordal distance less than 280 km), about 150 collocations are found.

Both bias and standard deviation of the retrieval minus radiosonde are reduced as compared with the background above 200 mbar in the Northern hemisphere (above latitude 30°N) and in the Tropics (between 30°S and 30°N). Figures 5-6 show the root-mean square (RMS) statistics for the guess, the analysis, and also a direct retrieval which assumed a humidity profile and was not constrained to a model background. Figure 7 shows an example of the capacity of the GPS to resolve the tropopause in the analysis. Both retrievals are able to see the colder tropopause measured by the radiosonde.

As expected for humidity, the analyses are very close to the guess except in the tropics. Figure 8 shows statistics for radiosonde collocations of humidity in the Tropics. The 1DVAR shows a slight improvement over the background in the lower troposphere. However, it should be noted that the sample size was small.

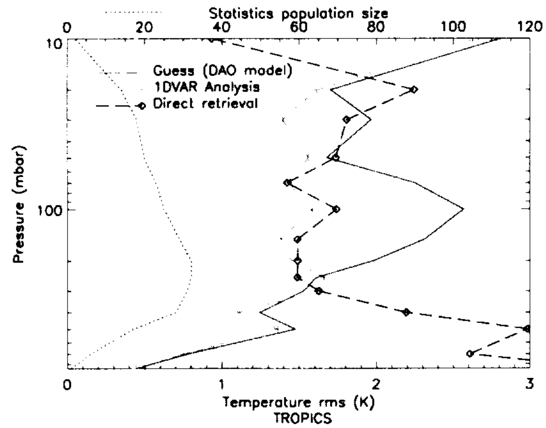

Figure 6: Similar to figure 5 but for the tropics.

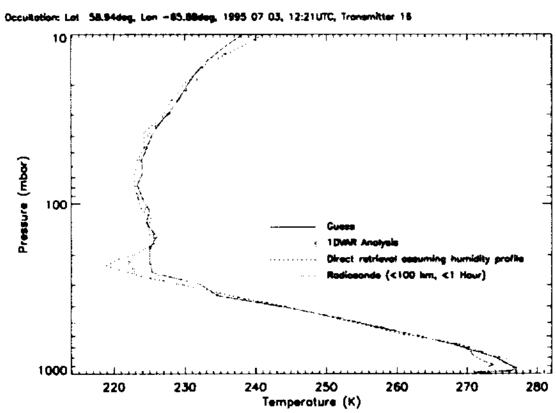

Figure 7: GPS temperature profile retrieval.

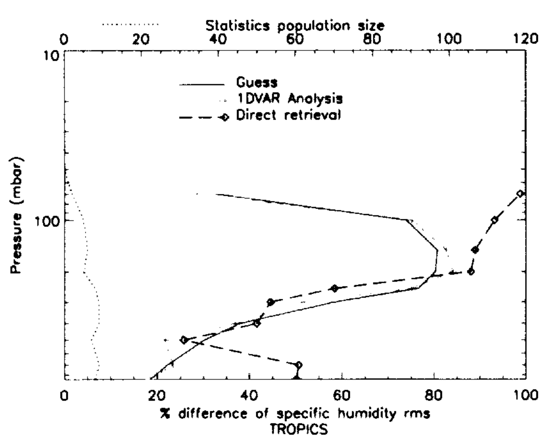

Figure 8: Similar to figure 6 but for percent of the specific humidity.

6. Conclusion and future work

We have shown that GPS measurements significantly improve analyses of temperature in the troposphere and in the lower stratosphere as compared with the model background. The 1DVAR appears to provide some humidity improvement resulting from the GPS data in the tropical lower troposphere.

We plan to conduct similar validation studies in the upper stratosphere for the temperature with other observing systems. We also plan to assimilate GPS retrieved temperature profiles in the GEOS-DAS for a period of time of at least fifteen days. We will assess the impact on the quality of medium-range predictions.

7. REFERENCES

Eyre, J. R., Kelly, G. A., McNally, A. P., Andersson, E., and A. Persson, 1993: Assimilation of TOVS radiance information through one-dimensional variational analysis. *Quart. J. Roy. Meteorol. Soc.*, **119**, 1427-1463.

Healy, S. B., and J. R. Eyre, 1999: Retrieving temperature, water vapour, and surface pressure information from refractive index profiles derived by radio occultation: a simulation study, *Quart. J. Roy. Meteorol. Soc.*, submitted.

Joiner, J. and L. Rokke, 1999: Variational cloud-clearing with TOVS data. *Quart. J. Roy. Meteorol. Soc.*, in press.

Kursinski, E. R., Hajj, G. A., Hardy, K. R., Schofield, J. T., and R. Linfield, 1997: Observing earth's atmosphere with radio occultation measurements using the global positioning system. *J. Geophys. Res.*, **102**, 23,429-23,465.

Rodgers, C. D., 1976: Retrieval of atmospheric temperature and composition from remote measurements of thermal radiation. *Rev. Geophys. Space Phys.*, **14**, 609-624.

Rodgers, C. D., 1990:Characterization and error analysis of profiles retrieved from remote sounding measurements. *J. Geophys. Res.*, **95**, 5587-5595.